LARGE SLOPES IN VENUSIAN LAYERED BASALT: TOO STABLE FOR FAILURE?,

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Summary

Magellan radar images reveal numerous slope failures on the Venusian surface. The nature of these failures can be surmised from the visible morphology and detailed topography of the slopes on which they reside [1]. These failures can provide illumination of the rock mass strength characteristics of the layered basalt of which these failed escarpments, and indeed most of the Venusian surface, are composed. To address this problem, slope stability analyses have been performed using slope models with dimensions known to exist on the Venus surface, and possible atmospheric influences were considered and factored into the evaluation. Instantaneous values of cohesion and internal friction for the rock mass were derived from Rock Mass Rating values [2,3] for the Venusian surface of between 25 and 75, [4], and utilized in the analysis. Results indicate stability under these conditions supporting the conclusion that, for the scarp geometries seen on Venus, slope failures within layered basalt result from a modification of the driving or resisting forces on potential failure surfaces and not an insufficient rock mass strength.

Circular Slope Failure

The first stability analysis utilized the Janbu method of slices to consider a circular or rotational failure mode. In this analysis the strength envelope was determined through computation of cohesion and internal friction values which yield a safety factor of one for an observed Venusian scarp having a height of 700 meters and slope of 60^o [5]. Conditions considered included scenarios incorporating no atmospheric influence on stability, a reduction in stability due to atmospherically induced pore pressures, and an increase in stability due to increased normal stress on the fault surface. Factor of safety in this analysis consisted of a comparison of the driving forces to the resisting forces acting upon a potential fault surface possessing the most unstable geometry. The driving force consists of gravity acting upon a volume of material defined by the sides of the escarpment and on the bottom by the potential failure surface. Resisting forces consist of cohesion and friction between fault surfaces and may be reduced by pore pressures which decrease the normal stress, or the presence of material possessing reduced cohesion or frictional values within the fault.

Subdivision of this volume into vertical slices, the bottoms of which are oriented tangential to the circular failure surface, allows analysis of the stability of each slice and summation of the results to yield a factor of safety for the failure as a whole. Many potential failure surfaces are analyzed, yielding one with the minimum, or critical, factor of safety.

This well known classical method for predicting landslide headscarps encounters some interesting difficulties when applied to layered basaltic rocks. Strength of the rock mass, even a heavily fractured one, greatly exceeds that necessary for failure while the substantial 9.8 MPa atmospheric surface pressure actually bestows a net increase in stability.

Wedge Failure

The second analysis considered wedge failure of a basaltic rock mass possessing no preexisting faults or zones of weakness. Again, stability was determined by comparing the sum of the driving forces, (gravity), to the sum of the resisting forces, (cohesion and friction), acting on the surfaces of potential faults [6]. The volume of failed material consists of a trapezoid, (fig. 1), which translates along an inclined failure surface. This geometry corresponds well with the columnar jointing commonly associated with basaltic flows and believed present on Venus. Instantaneous values of cohesion and friction for the rock mass are derived from the RMR values of 45 to 25 and normal stress acting on the potential fault surface as a function of the slide volume, surface area, and orientation of the failure plane under evaluation. Analysis produced factor of safety values for a wide range of potential fault orientations and failure volumes for both rock mass conditions, (fig. 2), none of which proved unstable due to the surprisingly large strength of these multilayered basalts.

Results

Paradoxically, none of the conditions considered in the first analysis was capable of yielding an unstable scarp. Venus's large 9.8 MPa atmospheric surface pressure produces a net gain of stability when considering the effects of induced pore pressures and increased normal stresses on potential failure surfaces. Likewise, analysis of possible wedge failures also show completely stable conditions within the modeled scarp even when using considerably reduced values of cohesion and friction corresponding to a highly fractured rock mass with joints oriented unfavorably, (RMR of 25).

These results agree with observations of layered basalt on Earth and Venus. Field observations of basaltic escarpments within the Snake River Gorge, Idaho, possessing heights over 250 meters and slopes occasionally exceeding 90^o show no mass movements of the types described above. Failures consisted of toppling on various scales and produced little of the dramatic reductions in slope angle associated with rotational or wedge failures, (fig. 3). Observations of Venusian mass movements reveal numerous situations in which a slope which has undergone failure exists adjacent to an unfailed escarpment possessing an even greater height and slope angle [1], or in which slopes of enormous dimensions exist without failure[5].

So how do they fail?

Stability analyses for circular and wedge failures within a layered basaltic rock mass reveals a stable condition for slopes with dimensions meeting and exceeding those common on Venus and Earth. This inherent stability requires a modification of driving or resisting forces to allow mass movements of the types seen in Magellan imagery. On Earth the gravitational driving force is most often augmented by high pore water pressures acting within joints to force movement along the failure surface or reduce normal stresses from the weight of the failure mass. With the absence of water on Venus this mechanism might rely on the high atmospheric pressures to reduce the normal stress on a potential fault surface. This would not augment the driving forces, however, and it is therefore reasonable to assume that a seismic moment due perhaps to volcanism, faulting, or impactor shock is responsible for the increase in driving force required for these failures. This same absence of water precludes the formation of clays or other slippery minerals within a fault in the manner common for earthly slope failures. Any analogous reduction of resisting forces within a Venusian fault must be due to some anhydrous weathering process or other mode of material emplacement resulting in a weak or slippery failure surface.

Analysis of regions surrounding Venusian mass movements may lend insight into the means by which failure was facilitated while proximity to volcanic regions, impact craters, or large faults might suggest sources for any seismic moments necessary for failure initiation. Back analysis of slide morphology using detailed topography yields required ground motion magnitude and thus displacement of a nearby fault. Numerous mass movements on volcanic flanks [1] may be due to a modification of both driving and resisting forces. The possible existence of steeply dipping ash deposits between basalt layers could significantly reduce resisting forces while seismicity of volcanic origin may provide the kick necessary for movement at these locations.

References [1] Malin, *JGR* **97**, 16,337, 1992 [2] Bieniawski, *Engineering Rock Mass Classifications*, Wiley, 1989. [3] Schultz, *Rock Mech. Rock Eng.* **28**, 1, 1995. [4] Schultz, *JGR* **98**, 10,883, 1993. [5] Connors, *JGR* **100**, 14,361, 1995. [6] Priest, *Discontinuity Analysis for Rock Engineering*, Chapman & Hall, 1993.

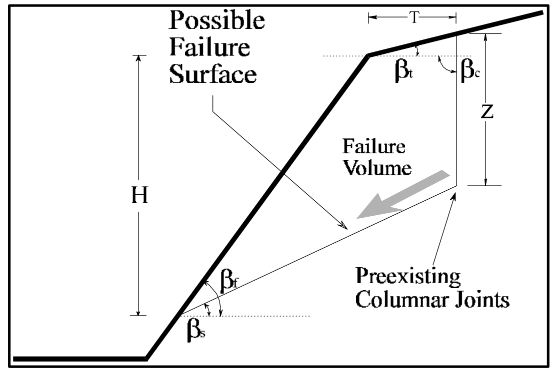

Figure 1. Geometry of wedge failure used in analysis 2. Vertical opening mode crack with length z could correspond to columnar jointing prevalent in multilayered basaltic rock masses.

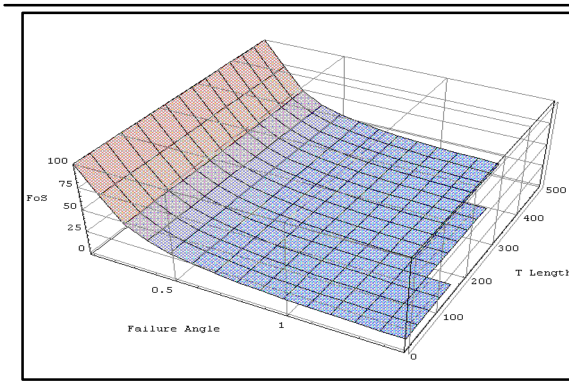

Figure 2. Factor of Safety calculations for spectrum of wedge failure geometries within heavily fractured basaltic rock mass with joints oriented unfavorably, (RMR 20).

Figure 3. Toppling failure example within the multilayered basalts of the Snake River Gorge, Idaho.